INFLIGHT ROTOR STABILITY MONITOR

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ABSTRACT

An inflight rotor stability monitor which has been developed at Sikorsky Aircraft to support stability testing of new rotorcraft is described. The monitor has as its core a damping estimation algorithm which embodies spectral analysis techniques. The interactive system is activated and controlled from a Cathode Ray Tube (CRT) and operates on-line in a flight test telemetry environment. Accurate estimates of the level of damping of critical system modes are generated within one minute of the completion of a prescribed test maneuver. The stability monitor has been used successfully during the past two years to support various Sikorsky research and development flight programs including the UTTAS, CH-53E, S-67 Fan-in-Fin, and ABC.

INTRODUCTION

One of the more difficult tasks the engineer is faced with is the identification and estimation of the level of damping of critical system modes from experimental data. His task is particularly formidable in the test environment where the pressure to make decisions quickly is high and the consequences of poor judgement may be severe. In the past, it was not uncommon for an engineer to be asked to bless the continued expansion of a test envelope with only time history oscillograph records from previous test conditions upon which to base his judgement. For well-behaved, lightly damped modes, which are sufficiently separated in frequency from other modes and forced response frequencies, real time filtering improved his capability of estimating damping levels. However, the effective use of filtering techniques required sinusoidal frequency sweep excitations or sufficient prior knowledge of the systems' characteristics to allow the use of bandpass filters. Sinusoidal sweep excitations are not always practical, particularly in flight. Also, filter rise times must be compatible with system time trends and sweeps rates in order to avoid overestimating damping because of spectrum averaging at critical frequencies. Of course, the overriding disadvantage of these techniques is that the engineer was still working with analog records which was very time consuming. Thus, most of his judgements were necessarily qualitative.

With the acquisition of the Real-Time Acquisition and Processing of Inflight Data (RAPID) system at Sikorsky Aircraft (see Reference 1) in the early 1970's, the avenue was paved for the development of improved inflight stability monitoring techniques. An inflight stability monitor was developed at Sikorsky in 1973 and has been used extensively for the past two years. It has as its core a

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modal damping estimation algorithm which is based on well-known spectral analysis techniques. The advantage of spectral analysis is that a time signal is transferred to the frequency domain where modal responses are separated from each other and from steady state responses. This permits easy identification of lightly damped system modes.

There is no one task in the stability monitor procedure which was particularily difficult to develop. On the contrary, each step is quite straightforward and easily achieved by standard methods. Even the damping estimation technique is now thought to be ubiquitous in the industry (see Reference 2) though a description of it is not known to be published in the literature. The real challenge in the development of the system was to make it work in the flight test telemetry environment. This involved providing adequate flexibility and accuracy while minimizing total time required to estimate system stability.

DESCRIPTION OF INFLIGHT STABILITY MONITOR SYSTEM

The Inflight Rotor Stability Monitor is an interactive system designed to provide an on-line stability estimation capability during the envelope expansion of new rotorcraft. The core of the system is the Sikorsky Aircraft ground station, RAPID, which consists of a SYSTEMS 86 computer with a full complement of standard and special peripheral devices (see Reference 1). The monitor involves two activities, the real-time acquisition, conditioning and calibration of measurements telemetered from an aircraft and the estimation of lightly damped modes of the test article from these data. The first of these steps is a standard function of the RAPID system. The damping estimates are made with a special purpose program designed to operate in telemetry environment during the short interval of time between test conditions. The stability monitor is shown schematically in Figure 1. During a flight, data are continuously transmitted to RAPID via telemetry. When a stability test is conducted, say for example the rotorcraft is excited by a control pulse, the engineer captures a "burst" of data by activating the Telemetry program from the CRT. The entire track of data (10 measurements) are digitized and calibrated (changed from volts to engineering units) in real time and stored on a disc. The Stability Estimation Program is then activated from the CRT. The program, which will be described in detail later, is highly interactive and consists of 3 steps: (1) review of the time data, (2) identification of critical system modes, and (3) calculation of the damping of these modes. The program is very flexible and very fast with the speed largely dependent upon the user's reaction time. Plots and printouts of pertinent data are program options. Upon the completion of the data processing, the user returns control of the system to the telemetry program for acquisition of another data burst.

The attributes which were considered important during the development of the Inflight Stability Monitor were speed, flexibility, and accuracy. The time required to estimate the damping of the critical system modes was the most important consideration. Since the program is an interburst processor, if the elapsed time required to complete the analysis is appreciably greater than the

time required by the pilot to set up for the next test point, total test time is increased resulting in increased risk and cost. One minute was targeted as the maximum allowable time for the computation of a damping estimate of a single critical mode. Minimum elapsed time actually achieved is approximately 30 seconds and depends largely upon the time share demands of the computer from the other sources when the On-line Stability Monitor is in use. One minute elapsed time is generally achievable regardless of the demands on the computer.

Since the times associated with computer calculations and data transfer are measured in micro- and milli-seconds and human response times are measured in seconds and minutes, effort was focused on speeding up the time required to make decisions by the users. The most important feature of the RAPID System which allowed the achievement of a one minute elapsed time for a damping estimate is the lightpen on the CRT.

Nearly all the decisions which have to be made interactively are done so with the lightpen. Options are preprogrammed and the user simply selects the options which fulfills his requirements with the lightpen. Sufficient latitude in the options is preprogrammed to handle most situations. Selecting an option is much faster than deciding what a value should be. Also activating the computer with the lightpen is faster than activation through a keyboard input.

Flexibility was also considered important during the development of the program. The ability to select from a number of different measurements and to choose a arbitrary section of the time data from the total record were requirements. It was reasoned that one would not always know, apriori, the measurement which responds the most in a mode so the ability to choose interactively was desirable. Also definition of mode shape and sensor reliability were factors which were considered.

The accuracy of the frequency and damping estimates were of course, of great importance. Desired accuracy was achieved by specific features in the actual algorithm developed to calculate modal damping.

DESCRIPTION OF STABILITY ESTIMATION PROGRAM

The stability estimation program involves three basic tasks:

Selection of time data for analysis
Identification of lightly damped modes
Calculation of damping

Each task has a CRT display associated with it and options which are exercised interactively to accomplish the task. The program can be best described by discussing each CRT display. The displays are from a typical rotorcraft application. The rotor is excited in flight with a longitudinal stick pulse. This control impulse generates a transient response of the rotor and airframe.

The first CRT display, Figure 2, is used to scan the time data and select an appropriate section of a measurement for further processing. The display is comprised of plotted time histories, a column of options to facilitate selection of specific data for further processing and print and plot options. Time histories of four parameters are displayed at a time. The program is sized to accomodate up to twenty signals with the NEW CURVES + - option, the vehicle by which different sets of curves are brought to the screen. The section of the burst of data which is displayed can be changed with the PAGE option, + to move forward in time and - to move backward. The length of the section of data displayed is arbitrary (within limits) and prescribed in the input data. The frequencies in the data and the sample rate are important considerations in sizing these initial time history displays. Generally, these time history curves are only used to find the transient response which is necessary for the damping calculation, so good signature is not required. The user prescribes the time at which he wants to start the analysis by keying in a value TO. The start time is usually when the system transient response to the excitation is a maximum. For the example shown TO = 2.65 sec is selected. The length of the data sample which is processed is prescribed by the number of points (2^N, N is an integer) and the SAMPLE RATE FOR ANALYSIS options. The total length of the data sample is:

$$T = (\text{SAMPLE RATE})(2^N)(\Delta t)$$

where Δt is the digitizing rate. The length of data determines the fundamental frequency $\omega_f = 1/T$ Hz and the achievable resolution in the spectral analysis which is performed next. 2^N data points are used because the FFT algorithm used for the spectral analysis is computationally most efficient with this constraint. The highest frequency in the spectral analysis is

$$\omega_{max} = 1/(\text{SAMPLE RATE})(\Delta t) \quad \text{Hz}$$

and must be selected to prevent aliasing of the data. In that respect, ω_{max} must be kept conveniently higher than the preprocessing filter bandwidth.

The measurement which is to be analyzed is selected with the CHOOSE CURVE option. A zero phase shaft digital band-pass filter can be applied to the data by prescribing a positive center frequency in the FILTER option. The filter roll off and bandwidth are prescribed in the input data. In general, the filter is not needed for accurate damping estimates except for those situations where the transient response signal to noise ratio is very poor.

It is worthwhile to note that default values for all options are specified in the program imput. Thus, if the user is familiar with his system's characteristics, his only actions are to select a start time (TO) and lightpen the CONTINUE option to proceed to the next step in the analysis.

The identification of lightly damped modes is performed in the frequency domain. A Fast Fourier Transform is used to calculate the discrete Fourier Transform of the time data sample selected. The magnitude of the transform is normalized to yield Fourier coefficients and plotted versus frequency in the second CRT display (Figure 3). A simple search routine is built into the

program to select peaks in the spectrum within a predetermined frequency range (input). These frequencies are ordered by their magnitude and displayed at the right of the plot.

For rotary wing applications, the system normally responds at harmonics of the rotor rotational frequency (forced response) and at natural modal frequencies if properly excited.* Prior knowledge of the system being tested makes identification of forced responses trivial and thus permits the easy recognition of significant transient modal responses. The user selects (light-pen) the frequency of the mode for which he wants a damping estimate with the PICK FREQUENCY option. He then can proceed to the damping estimation task by exercising the CONTINUE option. Should it be obvious to the user from the Fourier Transform plot that a significant transient modal response is not present in the signal, he may return to display 1 by activating the RETURN to A option. Records of the spectral data may be obtained with the PLOT & PRINT options.

It is worthwhile to note at this juncture the value of the Fourier Transform itself in dynamic testing. There are many situations when the test engineers task is to monitor for a transient modal response caused by random excitations during test envelope expansion. The Fourier Transform is an excellent tool for detecting such responses. Of course, the shape of the resonance peaks in the Fourier Transform can also be used directly to estimate modal damping if the system modes are sufficiently separated in frequency so that a single degree of freedom is approximated.

In the example shown in Figure 3, there are two modal responses, one at 7.0 Hz and the other at 6.0 Hz. The former is primarily a SAS/flapping mode and the latter a blade edgewise mode. The peaks at 4.9 H_Z and 9.8 H_Z are forced responses at one and two per rotor rev.

Before continuing to the description of the third CRT display it is timely to discuss the actual damping estimation procedure. Knowledge of the technique is a prerequisite to a meaningful discussion of the data on the third display.

Damping Estimation Procedure

Assume that there exists a time history of a signal which contains the transient response of one or more natural modes of a system. Assume further that the system is approximately linear. The damping of a mode (as defined by its frequency ω_o), can be estimated as follows. A percentage of the total data sample which comprises an integer number of cycles of the frequency of interest is first selected. The discrete Fourier coefficient $F(\omega_o)$ of this data sample is then calculated. Repeating this computation for similar blocks of data which are successively displaced in time generates the function $F(\omega_o)$

*An exception is when the system stability is governed by periodic coefficients in which case the modal frequencies can be at integer multiples of 1/2 the rotor frequency.

versus time. An estimate of the damping (ζ) of the mode is the slope of the curve $\ln F(\omega_o)$ vs time divided by the frequency ω_o.

If one accepts less than rigorous mathematics, the appropriateness of this procedure can be illustrated. Consider the damped sinusoidal function

$$f(t)=Ae^{-\zeta\omega_o t}\sin(\omega_o t+\phi)$$

The Fourier sine and cosine coefficients for N cycles of data starting at an arbitrary time t_o are defined as

$$a_1 = \frac{\omega_o}{\pi N}\int_{t_o}^{t_o+\frac{2\pi N}{\omega_o}} f(t)\cos(\omega_o t)dt$$

$$b_1 = \frac{\omega_o}{\pi N}\int_{t_o}^{t_o+\frac{2\pi N}{\omega_o}} f(t)\sin(\omega_o t)dt$$

Expanding these integrals and manipulating intensively, we arrive at two relatively simple expressions for a_1 and b_1:

$$a_1 = \frac{Ae^{-\zeta\omega_o t_o}}{2\pi N}(1-e^{-\zeta 2\pi N})\left\{\frac{\sin\phi}{\zeta} + \frac{[\zeta\sin(2\omega_o t_o+\phi)+2\cos(2\omega_o t_o+\phi)]}{\zeta^2+4}\right\}$$

$$b_1 = \frac{Ae^{-\zeta\omega_o t_o}}{2\pi N}(1-e^{-\zeta 2\pi N})\left\{\frac{\cos\phi}{\zeta} + \frac{[-\zeta\cos(2\omega_o t_o+\phi)+2\sin(2\omega_o t_o+\phi)]}{\zeta^2+4}\right\}$$

These can be combined to compute the magnitude of the Fourier coefficient

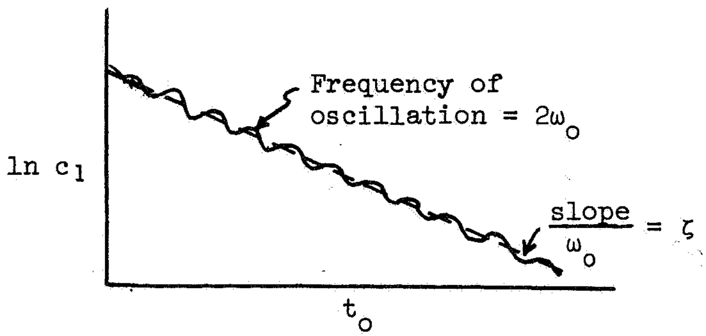
$$c_1 = \frac{Ae^{-\zeta\omega_o t_o}}{2\pi N}(1-e^{-\zeta 2\pi N})\Big[\frac{1}{\zeta^2} + \frac{1}{\zeta^2+4} - \frac{2}{\zeta^2+4}\cos(2\omega_o t_o+2\phi)$$

$$+ \frac{4}{\zeta(\zeta^2+4)}\sin(2\omega_o t_o+2\phi)\Big]^{\frac{1}{2}}$$

Rearranging, we see that c_1 has the same form as the original function $f(t)$; i.e.,

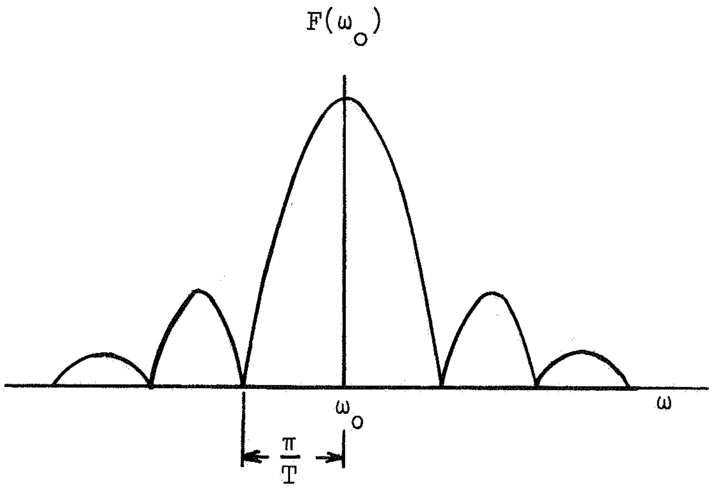
$$c_1 = Ke^{-\zeta\omega_o t_o}\sin(2\omega_o t_o+\Phi)$$

where K is a constant and Φ a phase angle which is of no concern. Thus, the envelope of decay of the Fourier coefficient c_1 is exactly the same as that of f(t). In the stability estimation program, the curve $\ln c_1$ vs t_o is developed and the linear slope divided by the modal frequency to obtain an estimation of ζ.



Inaccuracies in the Damping Estimate

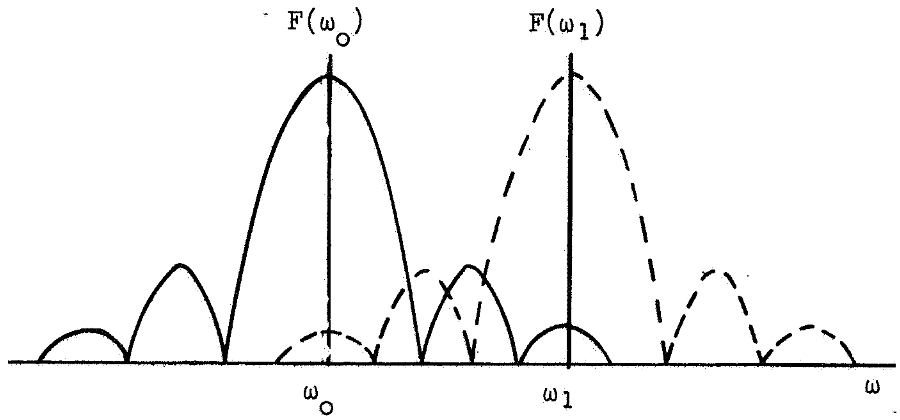
The major problem which is encountered in the damping estimation procedure arises because a typical time history response is composed of responses at several frequencies. Since finite length data samples are processed, frequency interaction occurs when the Fourier coefficients are calculated. The interaction is commonly called leakage and can be illustrated quite easily. If you calculate the Fourier transform of a simple sine function $f(t) = \sin \omega_o t$ for a data sample of finite length, it will have the following form:



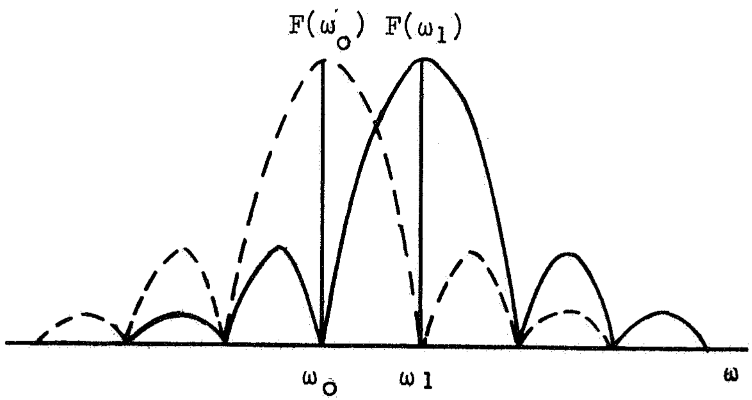
The maximum value of the transform will occur when $\omega = \omega_o$ and the sidelobes will be zero when

$$\omega - \omega_o = \frac{n\pi}{T} \quad (n = 1, 2, 3, \ldots)$$

If a signal contains two or more frequencies, the Fourier Transform is the summation of the transforms at each frequency. For example, the transforms of two sine waves having frequencies ω_o and ω_1 are sketched below.



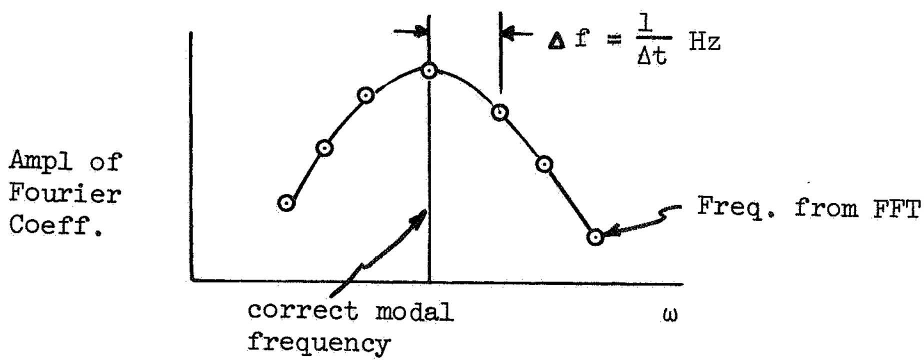
It can be seen that when summed, the sidelobs from one transform will affect the transform at the other frequency. This is exactly the phenomenon that occurs when the damping of a mode is computed when other frequencies are present in the time history. For many cases, the leakage has minimal effect; the frequencies are well separated, the magnitude of the response at the frequency of interest is large compared to other responses or the data sample is of sufficient length to minimize the magnitudes of the sidelobes. Difficulties arise when two or more frequencies are very close to each other or the magnitude of the modal response is small compared to other system responses. For the case of two frequencies which are close, the length of the data system can be adjusted so that the sidelobe from one frequency is zero at the other frequency, viz,



For this example, the Fourier analysis at ω_o is unaffected by the response at ω_1 and vice versa. For three or more frequencies which are close, the length of the data sample required to achieve similar decoupling may be impractical. For these cases, prefiltering of the data with low, high or bandpass digital filters may be required. Since filters have associated rise times, the damping estimates may have to be corrected accordingly. Another technique is to pass the data through a time window such as a Hanning window as a part of the damping estimation procedure. The effect of the window is to increase the rate of roll-off of the sidelobes at the expense of broading the main lobe.

Though all of these treatments of the data are possible, our experience has shown the satisfactory results are almost always achieved utilizing only the simple adjustment of sample length to decouple the frequency of interest from its major competing frequency.

With a general knowledge of the procedure used to estimate the damping of a mode, we are in a position to discuss the steps leading to the actual calculation. After a frequency has been selected from the second CRT display, an initial percentage (program input data) of the time signal is selected to form the data sample for the damping calculation. The frequency of the mode is then corrected. This is necessary because the FFT produces only 2^{N-1} spectral lines and the actual frequency of the mode can be expected to be between two lines. The adjustment of the frequency is accomplished by maximizing the magnitude of the Fourier coefficient as a function of frequency in the vicinity of the transform frequency. Very fine frequency changes are made by adjusting the length of the data sample by one point at a time. Thus, a curve of amplitude versus frequency is developed; i.e.,



and the corrected modal frequency determined. This same procedure is then applied to the frequency of the largest response in the signal within the designated frequency range and the sample length further adjusted to minimize the interaction of the two frequencies.

After these preparations are complete, the damping of the mode is calculated. The final CRT display (Figures 4 & 5) presents the estimated modal damping and data with which to judge its accuracy. Two figures are shown, one for each of the modes identified from the Fourier Transform. The display consists of a time history plot of the time data and a plot of the natural log of the Fourier coefficient versus time. Backtracking momentarily, it is recalled that the LOG_e (FC) curve is developed by performing repetative Fourier analyses of a fixed percentage of the total data sample which moves with time. For the examples shown approximately 70% of the record length formed the data sample which moved from t = 2.65 to t = 3.19, or 0.54 seconds.

As discussed earlier, the linear slope of the LOG_e (F.C.) vs time curve divided by the modal frequency is the modal damping. As a general rule, the more linear this curve, the better the damping estimate. In the right hand column of the display are printed the corrected modal frequency, the modal damping in decimal form and the standard deviation of the least squares linear curve fit through the Fourier analysis curve. The deviation is used as a measure of the accuracy of the damping estimate. There are occasions when it is obvious from the Fourier coefficient plot that the entire curve should not have been used for the damping estimate. Typical examples are starting the analysis before the transient response has built up to its maximum value or continuing the analysis beyond a time when the signal to noise ratio is acceptable. For such conditions, the EDIT feature can be used to prescribe the beginning (TO) and end (T1) of the Fourier coefficient curve for the damping estimate. When either TO and/or T1 are changed, the damping and standard deviation are automatically updated.

Several options are available to the user after he has completed his review of the damping estimate. There are the standard plot and print options which provide hard copy of pertinent data. The user may return to the Fourier Transform display (CHOOSE NEW W) to select another frequency for a damping estimate, or he may return to display 1 (CHOOSE NEW CURVES) to process another measurement or he may return to the telemetry program (RETURN TO T/M) to record another burst of data.

CONCLUDING REMARKS

During the past two years, the applications of the Inflight Stability Monitor at Sikorsky have been many. The first on-line application was the expansion of the CH-53E tail rotor stability envelope on a whirl stand. The estimated saving in test time on that program was 80% over the then accepted stability test techniques. Since that beginning, the system has been used to support the S-67 Blackhawk Fan-in-Fin, the UTTAS, the CH-53E, and ABC flight test programs. Confidence in the technique has grown and the system is fast becoming a standard tool for stability testing during aircraft development.

The stability estimation program has also received extensive use as an off-line diagnostic and data processing tool. It is operated off-line in RAPID in exactly the same way as it is on-line, with the source of time data an analog tape rather than telemetry. Off-line applications are typically modal damping calculations, mode shape definition and harmonic and spectral analyses. The program also receives extensive use as a post processor of time history data from analytical rotor simulation programs. For these applications at Sikorsky, a UNIVAC 1110 computer version of the program is available which is coupled with the simulation program. The total system is also a natural application for wind tunnel tests, especially if the facility has a dedicated digital computer.

REFERENCES

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2. Integrated Rotor/Body Loads Prediction, R. M. Carlson, A. W. Kerr, Presented at the AGARD Specialists Meeting on Helicopter Rotor Loads and Prediction Methods, Milan, Italy, March 30-31, 1973.

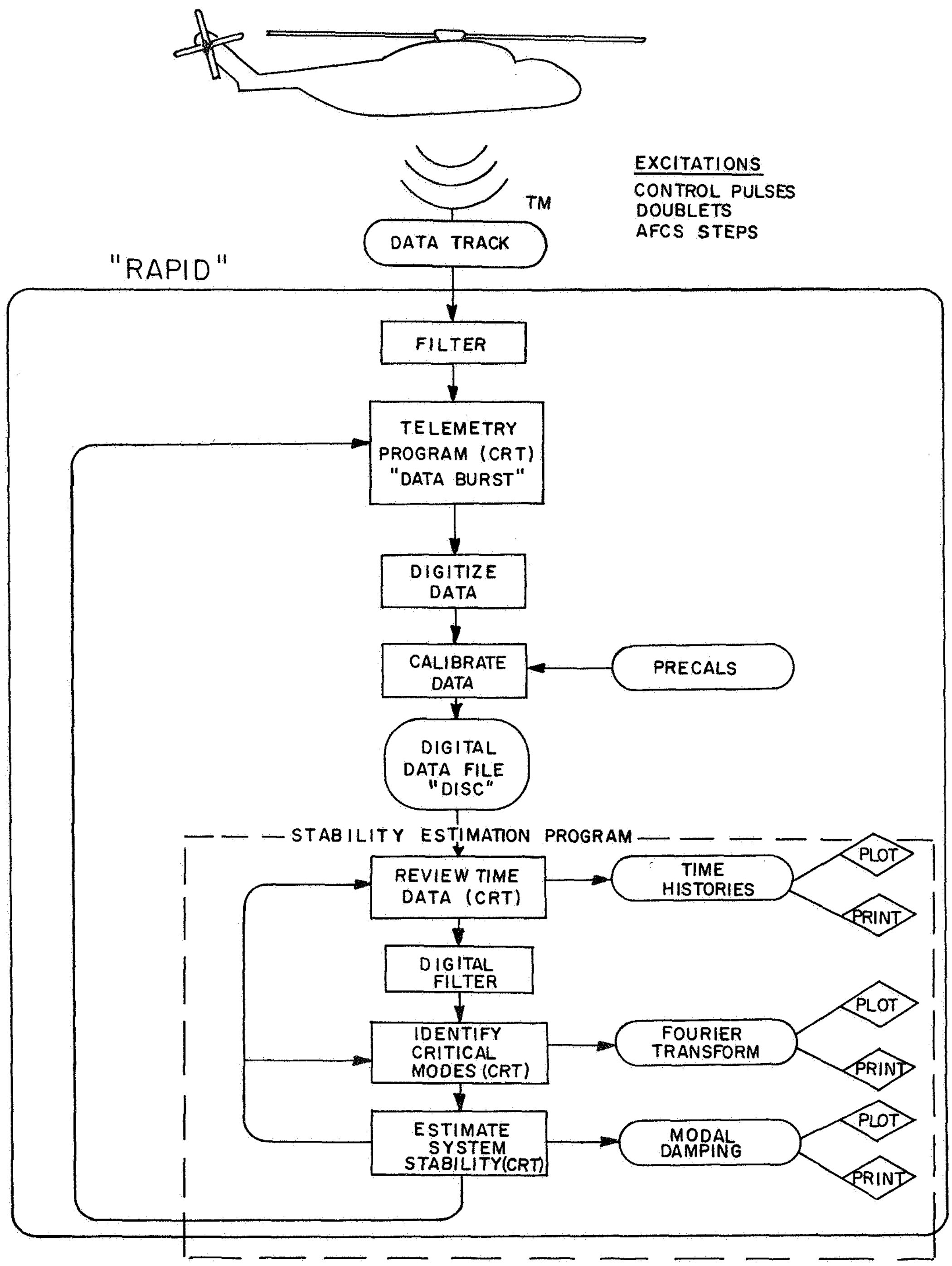

Figure 1 Inflight Rotor Stability Monitor Flow Chart.

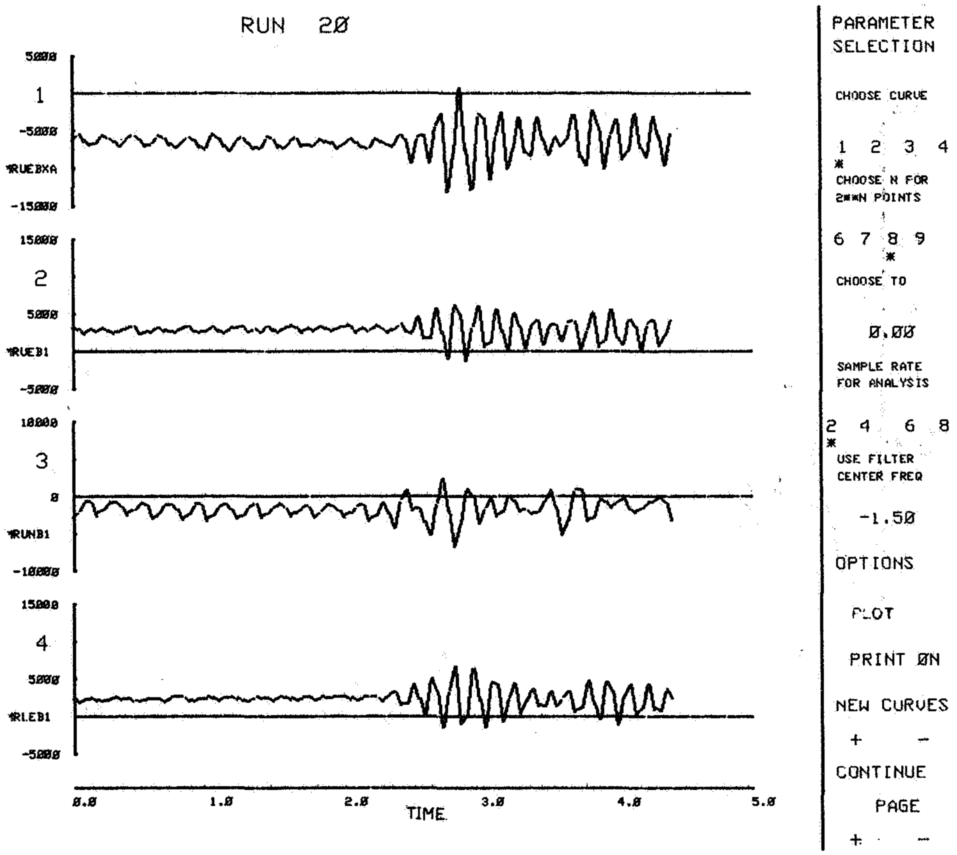

Figure 2 CRT Display 1, Time History Data.

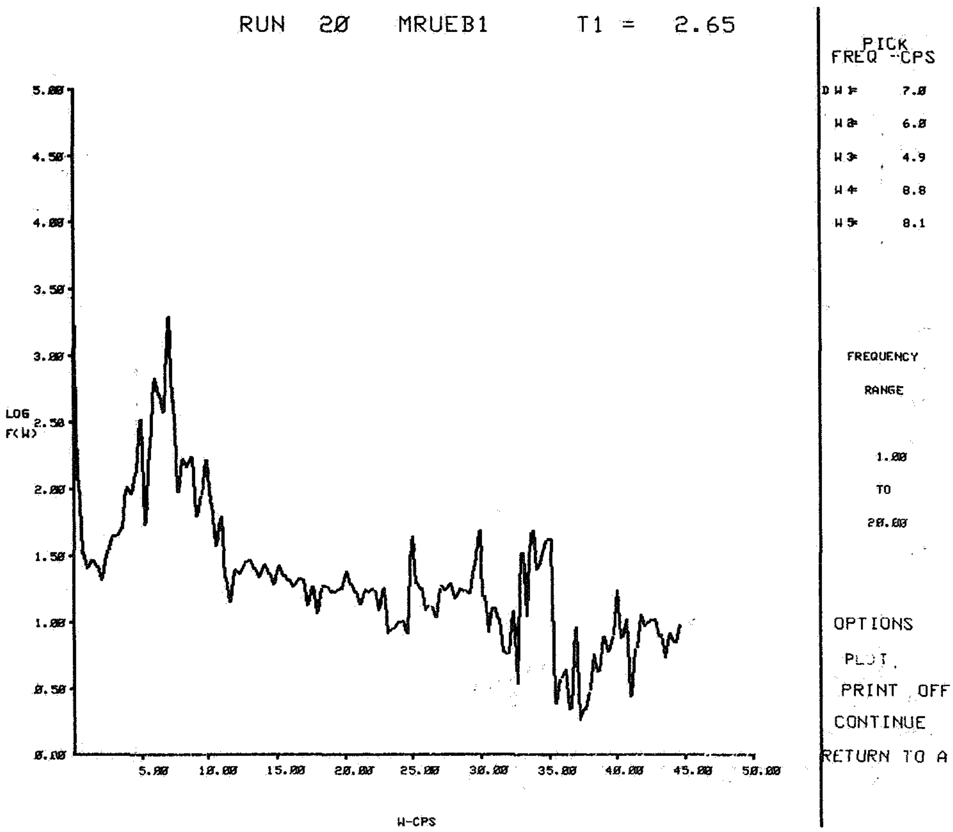

Figure 3 CRT Display 2, Magnitude of Fourier Transform.
(1 cps = 1 Hz.)

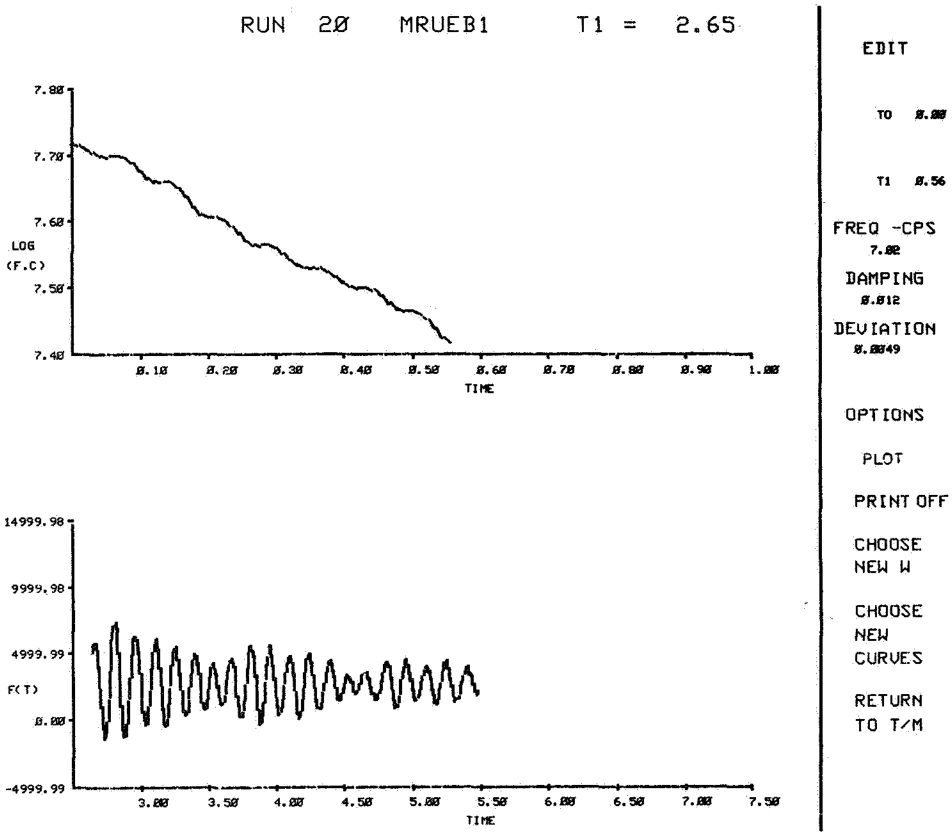

Figure 4 CRT Display 3. Modal Damping Estimate, ω = 7.02 Hz.

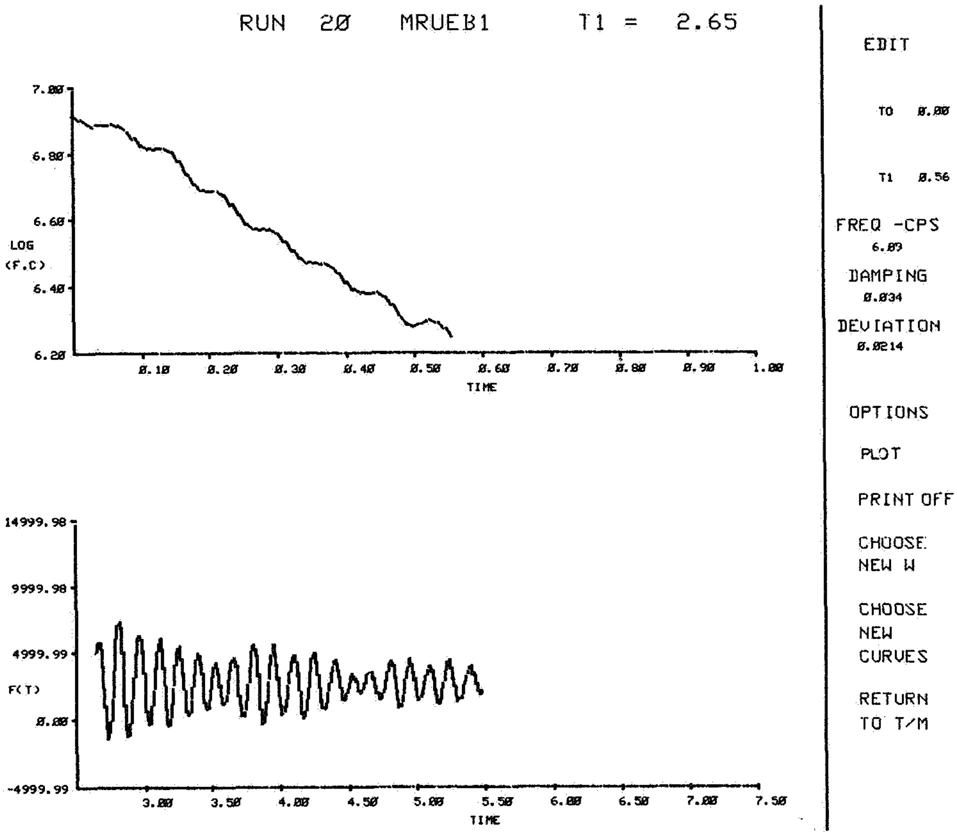

Figure 5 Modal Damping Estimate, ω = 6.09 Hz.